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A fully integrated 200 µW, 40pJ/b wireless transmitter for implanted medical devices and neural prostheses *

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Abstract— **In this paper we introduce a wireless transmitter suitable for implanted medical devices (IMDs) and neural prostheses. The transmitter achieves 500kbps data rate while consuming a peak power of 200 µW from a 1.2 V supply in a 130nm technology and has an active area of 35 µm by 45 µm. The transmitter works in the Medical Implant Communication Service (MICS) frequency band (401 – 406 MHz) and transmits the signal at a power of -20 dBm while achieves energy efficiency of 40pJ/b. The transmitter achieves this performance through a modified pulse position modulation called saturated analog signal (SAS) which has been tailored to reduce not only the peak and average power consumption but also helps reduces the number of elements required for signal generation and dispenses the need for a crystal which in turn minimizes the overall footprint of the transmitter. The transmitter can also dynamically trade off duty cycling and energy consumption with data rate and range requirements for better operability on a constantly changing environment due to the inherent flexibility of the modulation scheme.**

I. INTRODUCTION

Implantable medical devices (IMDs) and neural prostheses (NPs) have gained considerable research recently due to new advances in integrated circuit (IC) technology. The possibility of designing integrated systems on chips with reduced size and power has made them appropriate candidates for IMDs [2-6].

Although the small size and low power consumption are attractive characteristics of IMDs, these systems would best be exploited if they can communicate wirelessly with the external powerful Personal Computers, databases, etc. Wireless communication not only mitigates physical movement limitations of wires but also reduces the risk of infections and diseases [2, 5, 6].

Power consumption and data rates are among the most important factors in determining a suitable transmitter for IMDs and neural embedded systems. The retinal implants and brain machine interfaces (BMI) should provide greater than 500kbps for monitoring or stimulating an acceptable number of channels [2, 4, 6].

To power the implanted devices, either batteries or coils for wireless power transmission are used. The former has biocompatibility issues and might need to be periodically replaced which would render it not-ideal for surgically implanted devices and the latter has size limitations as well as significant coil misalignment penalties [2, 4, 6].

Another option is to harvest or scavenge the energy of the system from the environment. In all cases lower average power consumption per bit transferred is desirable, which is the focus of almost all recent studies; however an essential factor in all these design, which is often neglected, is the peak power consumption of the devices. Batteries for example can drain much faster if they are under higher current load than their nominal specifications and capacitors, used in many circuits as energy storage devices, show the same property if they are loaded beyond their specifications [11-13].

In this paper a new transmitter is introduced which has high data rate as well as low average and low peak power consumption. This is achieved through careful choice of modulation and architecture and also utilizing the low power consumption techniques in circuit design. The transmitter has been studied in detail and a prototype has been designed using the 130nm technology and the post-layout simulation results support the feasibility of the proposed technique.

The paper is organized as follow: in section II, the traditional modulation schemes are discussed and the modified modulation scheme is introduced. Section III explains the transmitter architecture and circuit design and in section IV conclusions are derived.

II. SATURATED ANALOG SIGNAL MODULATION

In biomedical applications and neural embedded systems, to achieve low power consumption, a less spectral efficient modulation scheme is used such as BFSK, BPSK or OOK [5, 14]. This is possible since most of the applications utilizing these modulations need low data rates (up to 300kbps). These systems fail to deliver higher data rates and hence researchers are utilizing ultra wide band (UWB) and impulse radio (IR) architectures to overcome the data rate problem while keeping the energy per bit transferred low [15, 16]. This is accomplished by heavily duty cycling the transmitter and utilizing high frequency short pulses (3.1-10.6 GHz) to transmit bursts of data. Although this technique has proven to be useful and can transmit high data rate with low energy per bit consumption, it needs powerful transmitter and have high peak powers. Also due to radio absorption in tissue at higher frequencies (greater than 1 GHz), the penetration range of such systems is extremely short (up to 1 cm) [7, 8]. Considering these limitations our proposed modulation scheme [17], which is a modified pulse position modulation, called saturated analog signal (SAS), utilizes the UWB like shorter pulses for duty cycling of the transmitter but operates in the MICS frequency band (401 – 406 MHz) for much better body penetration and achieves a 500kbps data rate. For more details on the modulation and the noise performance of

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the modulation the reader is referred to [17]. SAS also has inherent flexibility, where the data rate, duty cycling period and average energy consumption can all be changed dynamically to cope with the changes in surrounding environment and trades power consumption with data rate and range. This added flexibility not only benefits the transmitter but also it can be exploited for a robust, low power, high data rate receiver design and it enables the IMDs and NPs utilizing the modulation, to work in almost any environment.

III. TRANSMITTER DESIGN

The architecture of the transmitter is shown in Fig.1 and as can be seen the modulated data is directly sent to the antenna to avoid the power consumption of a power amplifier. This would restrict the amount of possible radiated power and the efficiency of the transmitter. Since this transmitter is for IMD or NP applications the radiated power allowed into the tissue is limited by regulations to -16dBm to comply with these regulations the transmitter has been designed to have a power output of less than -19dBm.

To modulate the data for transmission, and exploit the previously mentioned idea for a simple architecture transmitter, the duration of each data bit is divided into a predefined number of smaller, equal portions, called “bins”. To encode data, a sinusoid signal with a constant phase and frequency will appear in some of the bins. A combination of different bins containing the sinusoid will represent different data bits. An example of such signal, encoding two different bits is illustrated in Fig. 2. As can be seen in the diagram, the duration of each bit has been divided into 32 equal bins (3% duty cycle). In this example, bin 2 and 18 contain the sinusoid signal to represent a data bit of 1; and bin 5 and 10 contain the same sinusoid signal to represent a data bit of 0 (6% duty cycle). This signal is defined as follows:

$$g(t) = \begin{cases} A\cos(2\pi f_c t)\,rect\left(\dfrac{t-\frac{2T}{32}}{\frac{T}{32}}\right) + \\ A\cos(2\pi f_c t)\,rect\left(\dfrac{t-\frac{18T}{32}}{\frac{T}{32}}\right), & a_k = 1 \\ A\cos(2\pi f_c t)\,rect\left(\dfrac{t-\frac{5T}{32}}{\frac{T}{32}}\right) + \\ A\cos(2\pi f_c t)\,rect\left(\dfrac{t-\frac{10T}{32}}{\frac{T}{32}}\right), & a_k = 0 \end{cases} \tag{1}$$

The resulting power spectrum is illustrated in Fig.3 where the MICS frequency band (401-406MHz) has also been shown as an overlay to show the compatibility of this modulation for the designed frequency band.

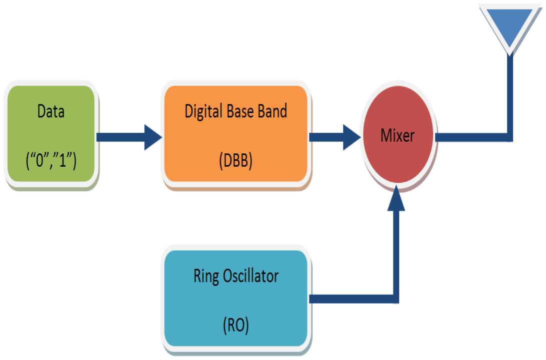

Figure 1.Transmitter architecture. The simplicity of the architecture is due to the underlying modulation scheme and not only reduces the size of the transmitter but also reduces the active components involved in the transmission and hence improves the energy efficiency of the transmitter

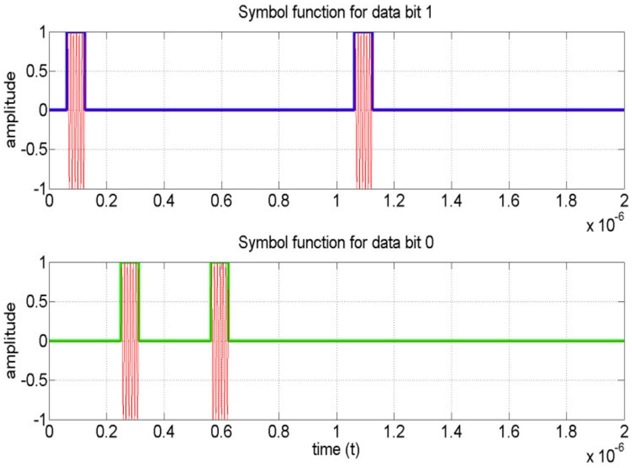

Figure 2. Sample symbol functions for a data bits. the first symbol function represents a data bit “1”. The second symbol function represents a data bit “0”

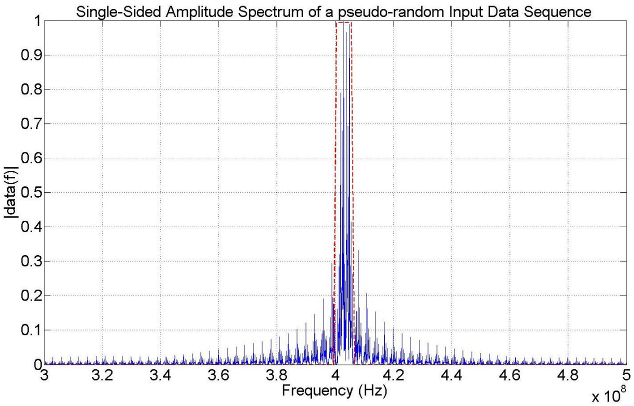

Figure 3. Power spectrum of a pseudo-random data stream modulated with a Saturated Analog Signal (SAS) modulation. The frequency band of MICS (401-406 MHz) is also shown as a dashed-line overlay.

The digital baseband inputs are (1) the data (at up to 500kbps), (2) the duty cycle period(1% – 95%), (3) the number of bins for each “0” or “1” logic symbol and (4) the carrier frequency as a clock. The number of bins depends on the available bandwidth and the required data rate and increases when either of the mentioned elements increases. The number of bins per logic defines the energy per bit consumption and duty cycling periods and also can be used to increase transmitted energy per bit for a more robust reception. The digital baseband signal also controls the duty cycling of the transmitter through power gating the RO and the mixer. The digital baseband section has been produced using verilog coding and standard cells in 130nm technolog. The resulting block consumes 40 µW of power from a 1.2 V supply when operating at 500kbps with a 402MHz carrier frequency. The block diagram of the digital baseband is shown in Fig.4

Since the SAS modulation is based on the position and number of the bins within each symbol, the frequency of the carrier need not be fixed as long as it can be kept in an acceptable MICS frequency range. Also as these transmitters are designed for IMDs and NPs and are implanted inside the body, the temperature of their environment is quite steady and the infrequent changes happen very gradually so a ring oscillator can be used to generate the carrier frequency to avoid the use of power hungry high precision phase locked loops (PLLs). In order to control the frequency of the ring the current of the ring oscillators are controlled through $V_{Control}$ and also a variable MOS capacitance is implemented inside the loop for further tuning of the loop frequency to set a 403 MHz carrier frequency. The schematic of the ring oscillator has been shown in Fig.5. To further decrease the power consumption of the transmitter, the mixer was realized as a passive mixer to consume only little leakage power while operating and was matched to the antenna with off-chip component.

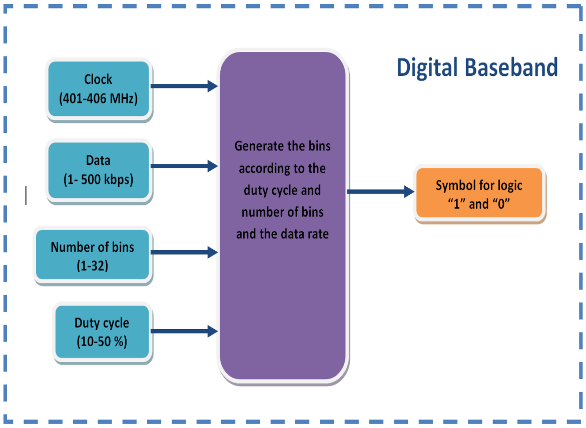

Figure 4. Digital Baseband (DBB) block diagram. Data input is at 1-500kbps and the clock reference is 403MHz (this clock can be in the range of 402-405 MHz). Also the duty cycle and the number of bins for each symbol can be changed dynamically according to the needs of the transmitter to trade off range and power consumption.

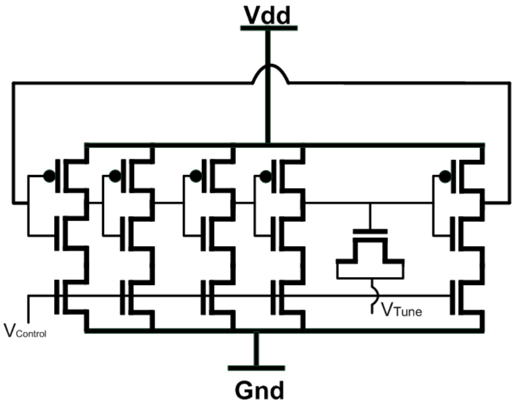

Figure 5. Voltage controled ring oscillator (VCRO) schematic. $V_{Control}$ controls the frequency of the ring oscillator through current control of the inverters and V_{tune} can further tune the frequency by adjusting the capacitance of the MOS device.

The transmitter performance has been summarized in table.I and also some state of the art transmitters from the literature have been compared with this work. As can be seen the transmitter achieves the best energy efficiency among the others while keeps the same communication range and acceptable output power. Some of the simulation results and the complete layout of the transmitter have also been shown in Fig. 6.

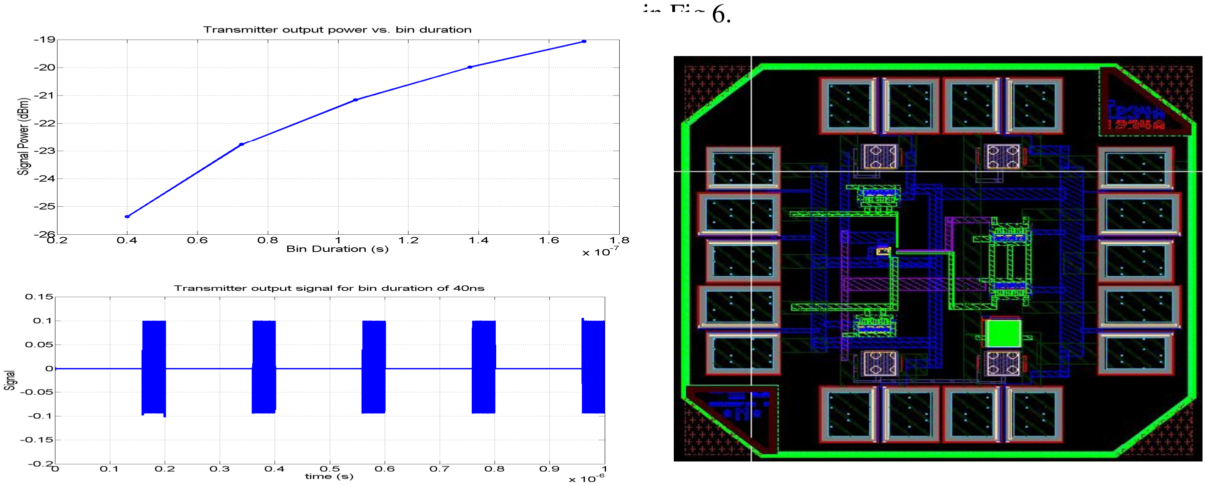

Figure 6. Simulation results of the transmitter. Up left figure shows the signal output power against the bin duration, which increases with bin duration. The left down figure illustrates a sample transmitted signal with bin duration of 40 ns and the right figure shows the complete layout of the transmitter.

TABLE I. TRANSMITTER PERFORMANCE COMPARISON

Reference	[1]	[7]	[8]	[9]	[10]	This Work
Transmit power (dBm)	1.4 - 11	-10	N/A	-5	-12.7	-20
Range(m)	3.2 - 4	20	0.01	2	3	5
Average Power(pJ/b)	1500	5916	343	1600	52	40
Peak Power	21mW	142mW	3.5mW	1.6mW	518 µW	200 µW
Data rate (bps)	14M	24M	10.2M	100K	10M	500K
Chip Area (mm2)	0.18	784	1.8	>7.8	1.76	0.53
Modulation	UWB(OOK)	FSK	Pulse Harmonic	BFSK	OOK	SAS
Technology	0.5 µm SOS	Components Off the Shelf (COTS)	0.5 µm CMOS	180 nm CMOS	0.35 µm CMOS	130 nm CMOS

The transmitter output power has been simulated against the bin duration for different values of bins (from 40ns – 170ns). The power would increase with bin duration as expected and hence the transmitter can trade off the transmission power and range with the energy efficiency and data ratealso an example of a transmitted signal is shown for a 40ns bin duration.

IV. CONCLUSION

In this paper a transmitter, suitable for implanted medical devices and neural prostheses, has been introduces and analysed. The transmitter consumes a peak power of 200 µW from a 1.2 V supply to achieve 500kbps data rate at -20dBm output power. The transmitter can achieve an energy efficiency of 40pJ/b transmitted data by exploiting duty cycling and has a 5m range. The transmitter is designed in the MICS frequency band (401 – 406 MHz) and has been laid out in 130 nm technology while occupying an active area of 35 µm* 45 µm and a total chip area (including test pads) of 0.16 mm^2. Also in this paper a previously defined modulation, SAS, is exploited, which provides the transmitter with a simplified architecture to save more energy and also reduces the footprint of the transmitter. The modulation also benefits an inherent flexibility, which provides transmitter with the possibility of working in different environments since the modulation can trades off energy consumption, duty cycling, range and data rate.

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